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Using the NPSS Environment to Model an Altitude Test Facility

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Abstract

An altitude test facility was modeled using Numerical Propulsion System Simulation (NPSS). This altitude test facility model represents the most detailed facility model developed in the NPSS architecture. The current paper demonstrates the use of the NPSS system to define the required operating range of a component for the facility. A significant number of additional component models were easily developed to complete the model. Discussed in this paper are the additional components developed and what was done in the development of these components.

Nomenclature

hp	horsepower
lbm	pound mass
rpm	revolutions per minute

Introduction

The NPSS environment was developed by an industry/government consortium and has become the environment of choice for numerical modeling of gas turbine engines, particularly for aerospace applications. However, its extreme flexibility has allowed it to be used in modeling a wide variety of thermodynamic systems. This paper, an extension of previously reported results (Ref. 1), presents additional information on the application of NPSS to a notional altitude facility. Included in this paper is a discussion of how to add new facility components (blowers or silencers, for example) and a parametric study of system performance highlighting how the model can be used to optimize the facility design or operation.

The Numerical Propulsion System Simulation

The NPSS environment is based on object oriented programming principles (Refs. 2 to 4). While models developed within this architecture are able to represent any engineering system, its primary function thus far has been in the development of performance models, largely for gas turbine engines.

All simulations are created from a collection including the simulation solver and five basic types (classes) of building blocks, which represent engine components, and describe how components are linked together. These classes are elements, subelements, flow stations, ports, and tables. Elements are primary building blocks connected to together by ports. They perform high level thermodynamic calculations. An example of an element would be a compressor or turbine block. Subelements are interchangeable secondary building blocks that are a part of elements or other subelements. An example of a subelement would be a machine specific compressor map calculation. Flow stations are responsible

for thermodynamic and continuity calculations. Ports provide linkages between the elements. There are four types of ports: mechanical, fluid, fuel, and thermal.

These objects can be assembled into system models that can realistically represent engineering systems of varying complexity. The input language of NPSS is very similar to C++ code. The objects used can either be part of the standard library package or can be custom elements developed outside of the main NPSS package.

The NPSS system is currently being used extensively in industry. Both General Electric (GE) and Pratt & Whitney (PW) are using the environment to support the simulation requirements of their new engine programs. The software is extremely flexible and can support all aspects of development program from conceptual design to transient performance modeling, engine test analysis, and data reduction. In addition, having a common tool between the companies has made teaming between companies on new engine projects much easier. For example, the GP7200 (a joint GE/PW effort to power the new Airbus A380 airplane), the F135 (PW engine for the Joint Strike Fighter (JSF)), and F136 (GE/Rolls Royce engine for the JSF) engines are current joint programs using the NPSS environment.

In addition to the increased fidelity that is possible, the companies have found advantages in the flexibility of the software. It is easy for the companies to implement their own algorithms at any desired location within the simulation. All that is required to create a new engineering element is to create a file which defines its ports, variables, and calculating function (description of its engineering processes). Since NPSS fully supports interpreted elements, it is not necessary to compile the new elements. The elements can just be read right in with the input file. In fact, all of the NPSS standard elements are released in both a compiled and interpreted form. The compiled form allows for speed. The interpreted form allows for easy customization.

Module Development

The NPSS software contains a wide variety of gas turbine engine and rocket engine components. A recently developed model of a closed cycle dual Brayton system required the enhancement of duct, heat exchanger, and heater modules (Ref. 2). These modules were easily adapted for use in the current facility model.

The model presented in this paper is a more complex and capable version of a facility model presented in Reference 1. Most components of the previous model were used in the formulation of the current model. However, modules for several components not available had to be developed. Creation of new components requires the addition of required calculations to a given basic element or perhaps the creation of an entirely new element. Changes or additions are made using language similar to C++. In addition to the liquid/gas heat exchanger, altitude chamber, and joiner element developed for the previous model, a silencer element and a blower element were developed. In addition, the altitude chamber was improved to allow a more realistic representation of freejet operation.

The blower element uses tables to look up pressure change versus blower speed. Massflow is a simple one-dimensional isentropic calculation using rotating speed and state variables, since a Roots blower is a constant displacement device where the flow is a linear function of rotational speed. Finally, the state variables on the downstream side of the blower (temperature and density) are calculated using one-dimensional isentropic flow equations.

The silencer is a modified duct element where the nondimensional pressure loss is either constant or calculated from an input table of pressure loss versus flow. State variables are calculated using one-dimensional adiabatic flow equations.

The modification to the altitude chamber involved the calculation of by-pass airflow. The earlier version of this model had a fixed bypass flow ratio. The current version uses engine airflow requirements, the altitude chamber state variables, and the prescribed velocity at the test article inlet face, along with test article and chamber geometry, to calculate the bypass flow.

The Model

Figure 1 is the graphical representation of the current model taken from the NPSS Graphical User Interface (GUI). In addition to the adding of silencers and a blower, the piping upstream is significantly more complex than previous models. The engine model used in this simulation contains 16 components. The previously reported facility model (Ref. 1) contains 54 components in addition to the engine model. The simulation discussed in this paper contains 65 components and the engine model. In addition, the model was simplified with respect to Reference 1 by the removal of one of the air chillers in the originally reported model.

Figure 1 shows the different regions and three specifically noted components (4 and two 9)

1. This region consists of the four compressors used when an atmospheric inlet will not provide adequate upstream conditions. The simulation in this region was simplified by removal of an extra temperature conditioning unit. This reflected a more reasonable engineering approach to the actual fabrication of an altitude chamber.
2. This is the atmospheric intake unit, which can be used for many chamber test conditions. No changes were made with respect to Reference 1.
3. This region is the heat exchanger for adjusting the intake air to the required temperature for the test.
4. An additional air heater has been added to this unit and the unit was repositioned so that it can condition air from either the atmospheric inlet source or the compressed air source, thus eliminating one heat exchanger from the model.
5. This is the intake ducting that leads from the air conditioning sections to the altitude chamber. This region has additional piping to represent the type of configuration that would be seen in reality and is significantly more complex.
6. This is the altitude chamber and the engine. It has an improved, more flexible method for calculating facility massflow.
7. This added heat exchanger is designed to adjust the air temperature to within a range acceptable for release into the atmosphere.
8. This region contains the additional blower and two silencers.
9. The addition of the blower completes the model. Rather than assuming the chamber exhaust is connected to an altitude exhaust system, the system now includes an altitude exhaust and may be considered self-contained.

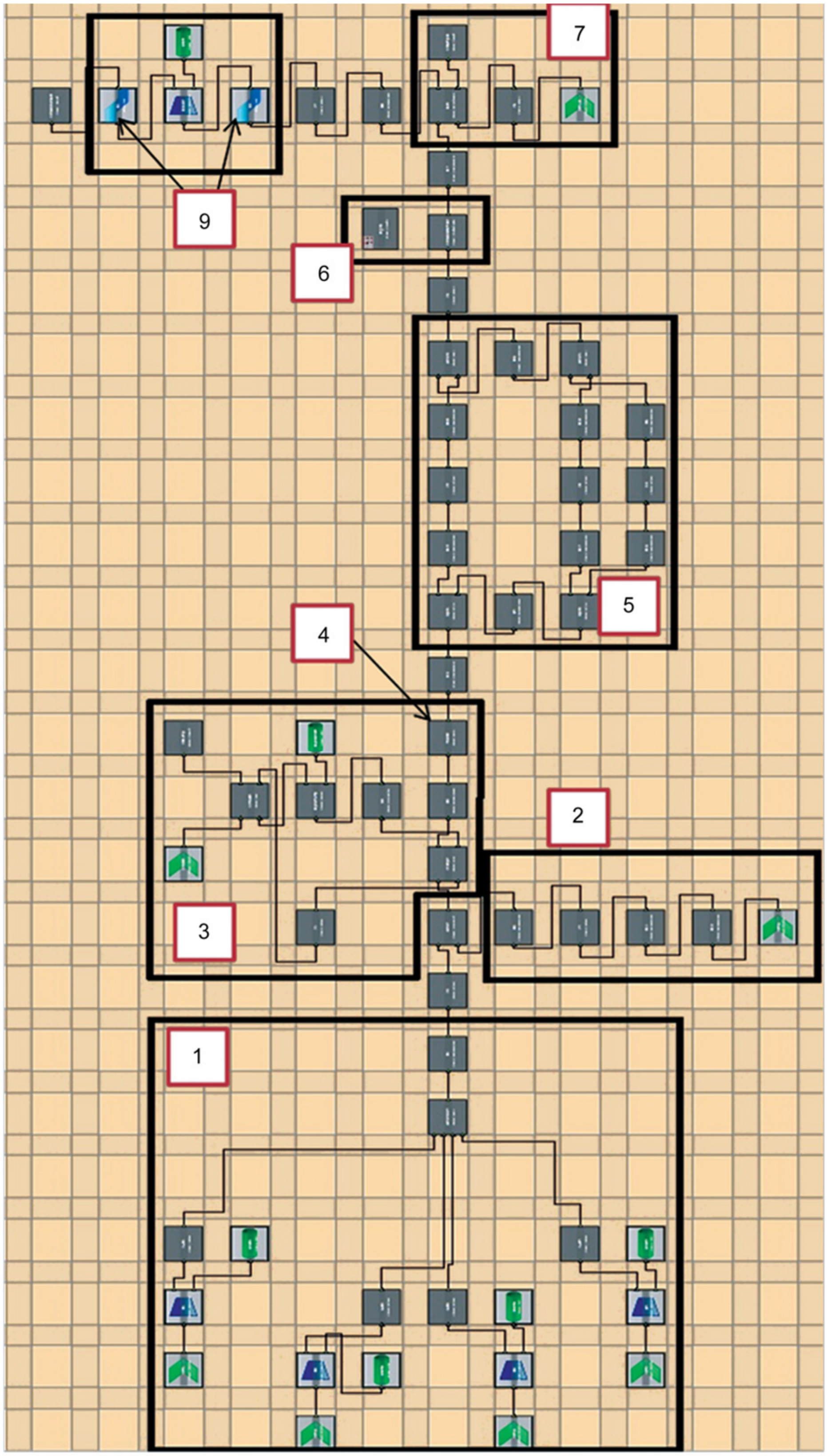

Figure 1.—Block diagram of combined model.

Model Operation

The model can be operated from either the command line or from the GUI. To vary the operating conditions of the model, the model file of the facility is opened. Any independent parameter can be varied but the parameters used for controlling this model are: engine speed and power, altitude chamber air velocity, altitude (total pressure) and total temperature, heat exchanger coolant and cooling air flows, and the number of facility compressors operating. In addition, outside air conditions can be specified for system operation at nonstandard conditions.

The model can be run either in the design mode or the off design mode. Operation in the design mode results in inlet compresser system sizing at the specified design point. Normally, however, the software is used in the off design mode to study the facility or component operation. Also, the simulation does not require a design point to be run. Existing systems and hardware can be simulated using existing performance maps and characteristics.

Model results are saved into an output file for command line operation or provided in a separate window during GUI operation.

Results

To demonstrate the capabilities of a facilities simulation, several parametric studies were completed. For the following parametric studies, the facility was configured with four continuous flow compressors. The test article was a 50 shaft horsepower (shp) notional turboshaft engine. The performance charts of the notional compressors for the facility were provided by Mr. Joseph Veres of the NASA Glenn Research Center (GRC) while Mr. Chris Snyder, also of GRC, provided the notional 50 shp gas turbine engine model.

Use of the compressers during facility operation allows a full range of operation of the altitude facility. However, under certain chamber conditions, the facility can use the available atmospheric inlet and not the compressor system, thus minimizing the cost of operation for a given test program. The first parametric study to be presented explores the limits of operation of the atmospheric inlet. For this study, the inlet and exhaust were specified to be standard day conditions. The chamber altitude and engine inlet Mach number were varied. Altitude chamber conditions used standard atmosphere conditions. The boundary between atmospheric inlet operation and inlet compressor operation was determined by either of two factors, altitude (the x-axis) and Mach number (the y-axis).

One occurred when altitude chamber temperature conditions required cooling of the inlet air provided by the atmospheric inlet. The other limiting condition occurred when the total pressure loss between the atmospheric inlet and the altitude chamber exceeded the required pressure difference in the altitude chamber. Figure 2 shows the result of this parametric study. As expected, atmospheric inlet operation is feasible at higher altitudes and, at lower altitudes, with higher Mach numbers. Thus the lower left hand

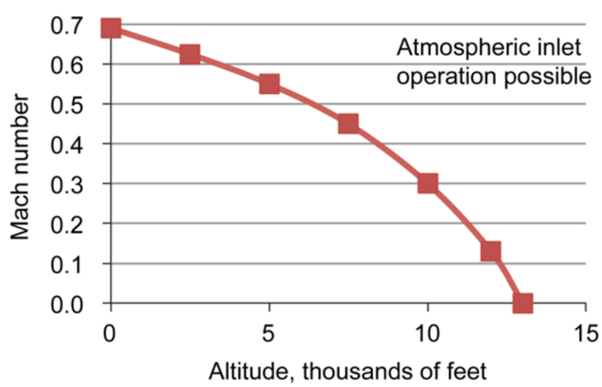

Figure 2.—Limits of atmospheric inlet operation.

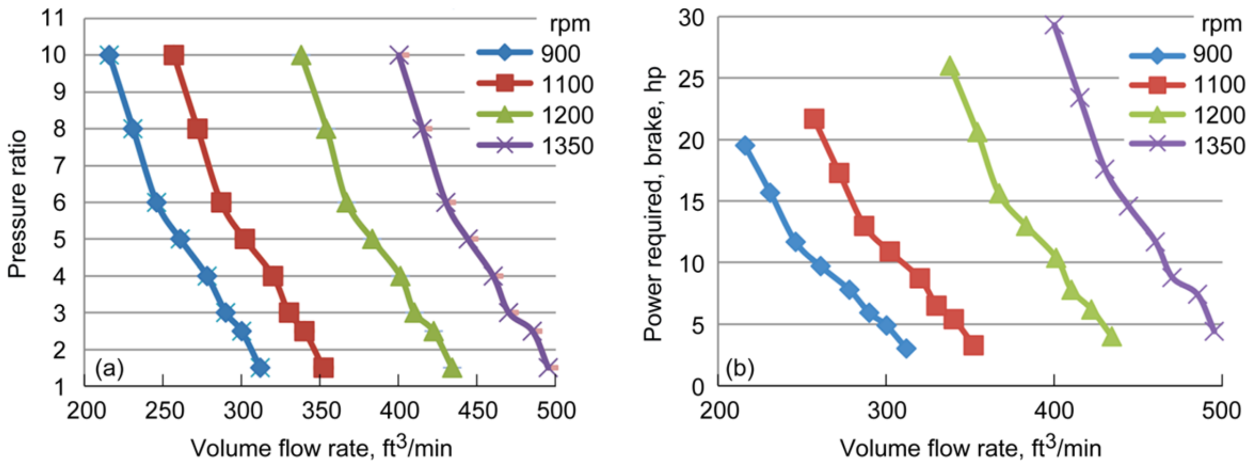

Figure 3.—(a) Pressure ratio versus flow rate. (b) Power required versus flow rate.

portion of the plot is the region where operation using the compressor system is required and the upper right hand portion of the plot is where operation with the atmospheric inlet is allowed. The model accounted for heat transfer to the environment outside the pipes and for pressure losses due to friction, sudden expansions, etc. Note that this simulation can be used prior to testing, if necessary, to determine if operation with the atmospheric inlet is feasible for a given set of test/facility conditions.

A second typical parametric study is the identification of the optimum operating point for the Roots blower at a given operating point in the altitude chamber. Figures 3(a) and (b) give the performance specifications of a typical roots blower. Selection of the blower operating point is a function of the required volume flow rate and the required chamber altitude (pressure). To determine the blower operating point, enter Figure 3(a) with the pressure ratio and flow rate. This provides the blower operating speed in revolutions per minute (rpm). Then use Figure 3(b) with the operating speed and volume flow rate to determine power required.

Figures 4(a) and (b) show the required blower power and speed for a given chamber altitude and Mach number. This output would allow the development of a blower operating schedule for a given altitude test or might aid in one of several potential machines to maximize system efficiency or operating costs. The calculated results for an optimization study looking at power required for given chamber operating conditions provided the results shown in Figures 4(a) and (b). Figure 4(a) shows that, at a given altitude, power required decreases slightly as Mach number increases. More striking is that the operating speed also decreases as Mach number increases as can be seen in Figure 4(b). These clearly counterintuitive results are a direct result of the chamber design and concept of operation. As initially implemented, this model performs as an altitude chamber where the airflow through the engine represents the airflow through the chamber. The turboshaft engine adds energy to the system, essentially acting as an air pump and reducing the power required from the exhaust pump (blower).

To further confirm the system operation, the altitude chamber representation was modified to reflect a “wind tunnel type” configuration. In this mode of operation, the physical configuration, in addition to the Mach number, defined the required airflow, not the engine airflow requirement.

Figures 5(a) and (b) show the results of a parameter study accomplished using this configuration.

Both blower speed and power requirements increase with increasing altitude and increasing Mach number. Clearly, the modification of the altitude chamber decoupling the engine air requirements from the airflow required to achieve a given engine intake condition results in chamber operation as expected.

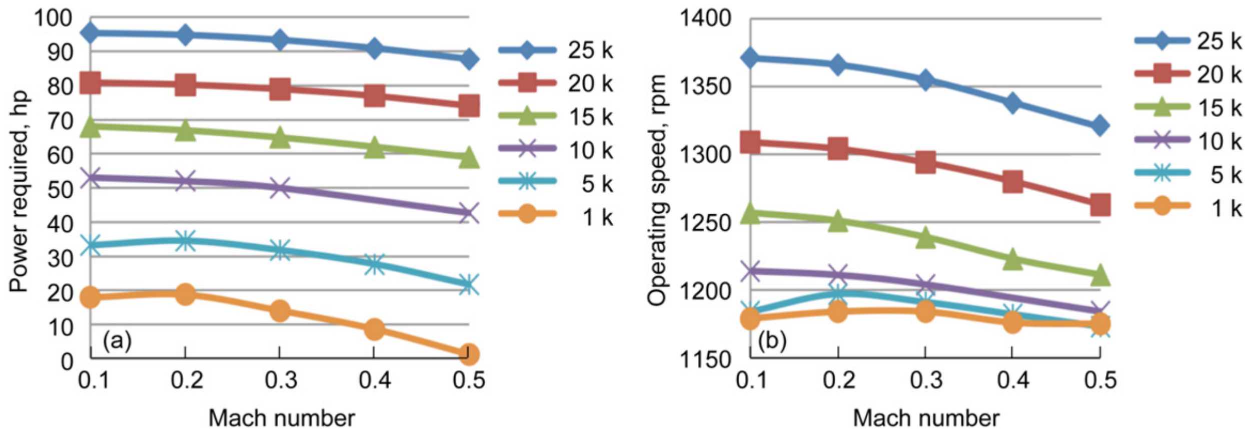

Figure 4.—(a) Power versus Mach number. (b) Operating speed versus Mach number.

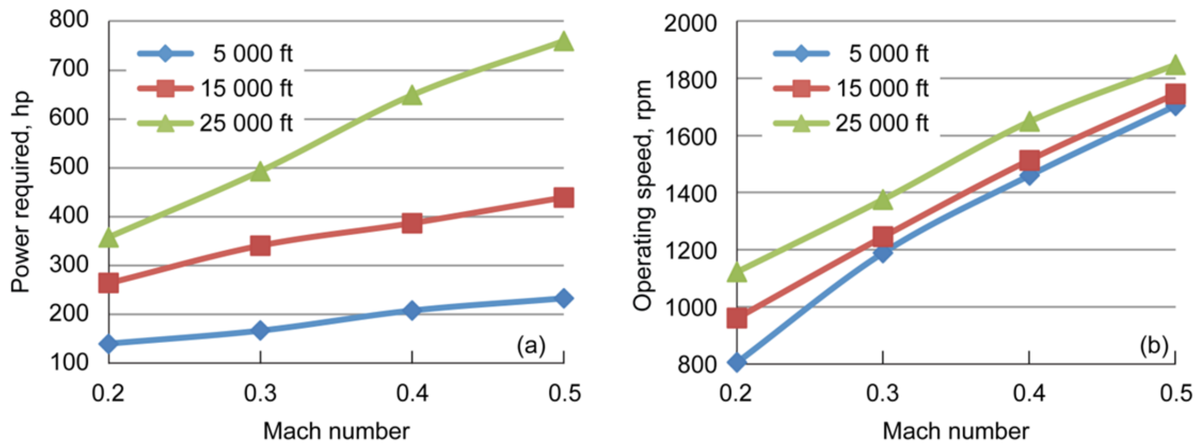

Figure 5.—(a) Power versus Mach number. (b) Operating speed versus Mach number.

Summary and Conclusions

A complex system simulation of an altitude test facility has been developed using the NPSS modeling environment and tested. This simulation includes an engine system model. The facility model developed can easily accommodate various engine simulations and chamber operating modes. This simulation can be used to size facility components and for parametric studies to optimize operating configurations for different test parameters.

This paper presents the results of several parametric studies using this simulation. The results of one study provided an operating boundary for this system using conditioned air acquired directly from the environment and air requiring compression before conditioning to allow the system to meet required altitude chamber conditions. A second study provided the required operating points and required power for the Roots blower at given altitude chamber operating conditions.

Another unique result of these studies is the observation that the engine in the altitude chamber can be a significant component of the system being modeled and cannot simply be ignored. This component can provide significant energy to the air and can substantially affect the power requirements of the downstream blower system.

The NPSS environment is extremely flexible and has been demonstrated to be able to numerically replicate a highly complex fluid system.

References

1. Huffman, Brian C., Lavelle, Thomas M., Owen, Albert K., "An NPSS Model of a Proposed Altitude Test Facility," 49th AIAA Aerospace Sciences Meeting, 4–7 Jan 2011, AIAA–2011–312.
2. T.M. Lavelle, S. Khandelwal, A.K. Owen, "Intermediate Fidelity Closed Brayton Cycle Power Conversion Model," NASA/TM—2006-213993 (National Aeronautics and Space Administration, Glenn Research Center, Cleveland, OH, 2006).
3. NPSS User's Guide and Reference, NASA Publication, 2002.
4. J.K. Lytle, "The Numerical Propulsion System Simulation: An Overview," NASA/TM—2000-209915 (National Aeronautics and Space Administration, Glenn Research Center, Cleveland, OH, 2000).
5. Binder, M.: Numerical Propulsion System Simulation Introduction. Multimedia CD, 2000. Available from the NASA Glenn Computing and Interdisciplinary Systems Office.

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